The Thermal Efficiency of the Rotary Cement Kiln.*

By HANS GYGI (Zurich.)

IV.—HEAT TRANSFER (*Concluded*).

(4) Heat Transfer in the Burning Zone.

The heat transfer in the burning zone can also be calculated if we use the gas temperatures calculated in our investigation of the processes of combustion in place of the actual temperatures which it is not possible to measure in this part of the kiln.   An attempt will now be made to calculate the heat transfer at cross section II.

(I).—CALCULATION OF THE HEAT TRANSFER FROM THE GASES FOR I M. LENGTH OF KILN.—Heat is transferred from the gas to the lining (wall) and to the material by radiation from the gases and from the particles of coke, and also to the lining and to the material by convection.   The process can be expressed as

$$Q_{Gas} = Q_{Radiation\ G.W} + Q_{Radiation\ G.M.} + Q_{Radiation\ C.W} + Q_{Radiation\ G.M.} + Q_{Convection\ G.W.} + Q_{Convection\ G.M.}$$

In the pre-heating zone we were concerned merely with radiation from the gases, but here we must take the radiation from the particles of coke into account. This can be done by means of the law enunciated by Stephan and Boltzmann, but it must be borne in mind that a considerable proportion of the radiation emitted by the coke particles impinges on other particles before it reaches the wall and will be absorbed.   W. Nusselt[25] has allowed for this phenomenon by means of the angular ratio ϕ and has given the method for the approximate calculation of ϕ which is described here.

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* Concluded from our issues for November and December, 1937, and February, March, April and June, 1938.
[25] W. Nusselt, "Zeitschrift des Vereins Deutscher Ingenieure," page 124 (1924).

Let 1m.^{3} of dust-gas mixture contain n particles. Assuming a uniform mixture, each particle is contained within a cube whose side is

$$l = \sqrt[3]{\frac{1}{n}} \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (42)$$

The particle can take up any position within the cube. Let us consider a few of such cubes. The number of cubes will be

$$N = \frac{1}{l} = \sqrt[3]{n} \quad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (43)$$

In each cube there is a particle of coke. If heat radiates through this row of cubes part of the radiation will be absorbed by the coke particles and of the cross section l^2 of the incident beam of radiation only the fraction ψl^2 penetrates the entire row of cubes. For the approximate calculation of ϕ let it be assumed that a coke particle having a radius r cannot take up any arbitrary position within the cube whose side is l. The cross section l^2 of the cube can be conceived as being sub-divided into

$$m = \frac{l^2}{r^2 \pi} \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (44)$$

cells, and it may be assumed that the coke particle must lie in one of these cells in the cross section l^2. Let each cube be divided into m such cells and let these cells be numbered from 1 to m. In every case the coke particle belonging to the cube will take up its position in one or other of the cells.

According to the theory of probability the number of rows of unoccupied cells will be

$$m \left(1 - \frac{1}{m} \right)^N$$

and, therefore

$$\psi = \left(1 - \frac{1}{m} \right)^N \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (45)$$

Let the coefficient for the absorption of radiant heat by the pulverised coal mixture be a, and

$$e^{-a} = \psi$$

or

$$a = ln \frac{1}{\psi} \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (46)$$

The angular ratio for the radiation from a particle of coal is then

$$\phi = \frac{1}{4\pi} \int_0^{4\pi} e^{-a} y \, d\omega \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \quad (47)$$

in which y is the length of the path of the radiation from the particle under consideration through the mixture of coal dust and air to the wall of the combustion chamber and $d\omega$ is the solid angle of the beam of radiation.

For the numerical calculation of the angular ratio we must know the size and number of the coal particles and the shape of the flame. The fineness of the coal used in the present experiments was about the same as that of the dust on which

W. J. Wohlenberg based his investigation, so that the mean diameter of the coal particles may be taken as $d_0 = 0.002$ in. Wohlenberg calculated a shrinkage factor for the coal particles of mean diameter d_0 from the volatile and moisture contents of the coal and the specific gravities of coal and coke, and so obtained a mean diameter, d_1, for the coke particles and proceeded to determine the angular ratio for this particle size.

The shrinkage factor for the coal used in these experiments is 0.95, so that the mean diameter of the coke particles is 4.83×10^{-5}. The number of coke particles contained in 1m^3 of flame can be calculated from the coal consumption of the kiln, the shape of the flame, and the conditions under which the coal dust is introduced into the combustion chamber. The number of particles is

$$5.496 \times 10^8 / \text{m}^3$$

and the surface of the particles

$$4.028 \text{ m}^2 / \text{m}^3.$$

By substituting $y = 1$ m. in equation (47) we obtain

$$\phi = 0.3651$$

for the value of the angular ratio.

The angular ratio being known we can calculate the radiation from the coke particles by the method of Stephan and Boltzmann. A portion of the radiation,
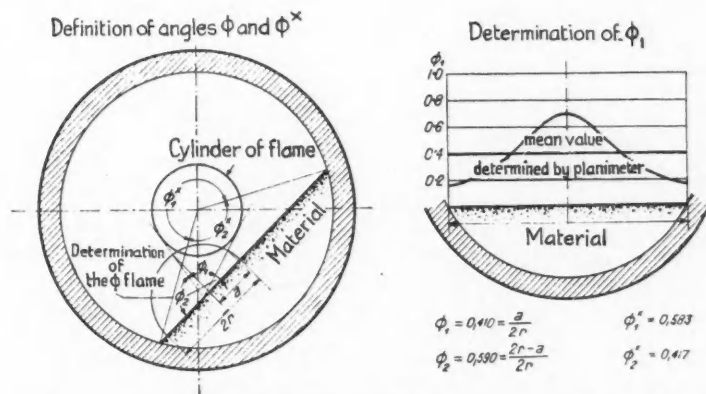

Fig. 26.—Determination of the solid angles ϕ_1 and ϕ_2, and $\phi_1{}^*$ and $\phi_2{}^*$ at cross-section No. 11.

however, is absorbed by the gases and for this reason the " permeation coefficient " must again be introduced into the equation. Finally, we must take into account the angle ϕ^*, determined graphically in *Fig.* 26, according to whether we are dealing with the heat radiated to the wall or the heat radiated to the material. We may now proceed to the numerical calculation of the various terms of equation (41).

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The temperatures of the gases, the wall, and the material at cross section 11 are as follows :

Mean gas temperature .. .. t_g = 1,845 deg. C.
Mean temperature of exposed lining .. .. .. t_w = 1,330 deg. C.
Temperature of material .. .. t_m = 901 deg. C.

The products of the partial vapour pressures of the carbon dioxide and the water vapour multiplied by the thickness of the layer are

$$c^2CO_2 = 0\cdot23$$
$$c^lH_2O = 0\cdot07$$

Q Radiation G.W.

$$\text{Kcal./m.}^2\text{h.}$$
$$q_{CO_2} = 25,000$$
$$q_{H_2O} \cdots 32,400$$
$$\overline{}$$
$$q_{G.W.} = 58,100 \text{ Kcal./m.}^2\text{h.}$$
$$Q_{G.W.} = q_{G.W.} \times F_w.$$

F_w, the surface of exposed lining for 1 m. length of kiln, is 5·13 m.²

$$Q \text{ Radiation G.W.} = 298,000 \text{ kcal./m.h.}$$

Q Radiation G.M.

$$\text{Kcal. /m.}^2\text{h.}$$
$$q_{CO_2} = 39,600$$
$$q_{H_2O} = 50,400$$
$$\overline{}$$
$$q_{G.M.} = 90,000 \text{ Kcal./m}^2\text{.h.}$$
$$Q_{G.M.} = q_{G.M.} \times F_m.$$

F_m, the surface of the material for 1 m. length of kiln, is 3.67 m.²

$$Q \text{ Radiation G.M.} = 330,000 \text{ Kcal./m.h.}$$

Q Radiation C.W.

Having regard to the general consideration mentioned, the equation of Stephan and Boltzmann may be written as follows for the case under consideration :

$$Q \text{ Radiation C.W.} = \phi . F_e . C \left[\left(\frac{T_{Fe}}{100}\right)^4 . \rho_{Fl} - \left(\frac{Tw}{100}\right)^4 . \rho_w \right] . \phi^* \quad .. \quad .. \quad .. \quad (48)$$

Equation (48) is only valid if analogous assumptions are made to those discussed in connection with equation (25). As these assumptions are in fact not quite accurate the equation is only approximate.

F_k is the surface of the coke particles in 1 m. length of flame volume. The flame temperature (T_{Fl}) is the temperature at the axis of the flame which we have already calculated from the mean combustion factor and the heat evolved. The method of determining ϕ^*_1 is shown in *Fig. 26*.

$$F_k = 2\cdot284 \text{ m.}^2$$
$$T_{Fl} = 2,357 \text{ deg. C.}$$

and substituting

$$Q \text{ Radiation C.W.} = 0\cdot3651 \times 2\cdot284 \times 4\cdot70 \left[\left(\frac{2357}{100}\right)^4 \times 0\cdot893 - \left(\frac{1603}{100}\right)^4 \times 0\cdot821 \right] \times 0\cdot583.$$
$$Q \text{ Radiation C.W.} = 508,000 \text{ Kcal./m.h.}$$

Q Radiation C.M.—The expression for the radiation from the coke particles to the material is

$$Q_{\text{Radiation C.M.}} = \dot\phi \cdot F_k \cdot C\left[\left(\frac{T_{Fe}}{100}\right)^4 \cdot \rho_{Fe} - \left(\frac{T_m}{100}\right)^4 \cdot \rho_m\right] \cdot \phi^*_2 \quad .. \quad .. \quad (49)$$

after determining ϕ^*_2 from *Fig.* 26 and substituting

$$Q_{\text{Radiation C.M.}} = 0\cdot3651 \times 2\cdot284 \times 4\cdot70\left[\left(\frac{2357}{100}\right)^4 \times 0\cdot893 - \left(\frac{1174}{100}\right)^4 \times 0\cdot759\right] \times 0\cdot417.$$

$Q_{\text{Radiation C.M.}} = 428,000$ Kcal./m.h.

$Q_{\text{Convection G.W.}}$—$Q_{\text{Convection G.W.}} = \alpha(t_g - t_w)F_w$

For the heat transfer coefficient $\alpha = 4\cdot41$ Kcal./m.²h. deg. C. we have

$$Q_{\text{Convection G.W.}} = 11,650 \text{ Kcal./m.h.}$$

$Q_{\text{Convection G.M.}}$—$Q_{\text{Convection G.M.}} = \alpha(t_g - t_m)F_m$

$$Q_{\text{Convection G.M.}} = 15,260 \text{ Kcal./m.h.}$$

Thus, for the total heat transferred from the gases for 1 m. of kiln length we have :

Kcal./m.h.

$Q_{\text{Radiation G.W.}} = 298,000$

$Q_{\text{Radiation G.M.}} = 330,000$

$Q_{\text{Radiation C.W.}} = 508,000$

$Q_{\text{Radiation C.M.}} = 428,000$

$Q_{\text{Convection G.W.}} = 12,000$

$Q_{\text{Convection G.M.}} = 15,000$

$Q_{\text{Gas calculated}} = 1,591,000$ Kcal./m.h.

The experimental determination of heat transfer for the cross section under consideration gave $Q_{\text{Gas experimental}} = 2,009,000$ Kcal./m.h., so that the calculation did not comprise all the heat given off by the gases and the coke particles. The discrepancy between the calculated and the experimental values is probaby due, in this cross section also, to the fact that no allowance was made in the calculation for the radiation from the dust particles suspended in the gases.

(2).—CALCULATION OF THE QUANTITY OF HEAT TRANSFERRED TO THE MATERIAL IN 1 M. LENGTH OF KILN.—Heat is transferred to the material by radiation from the gases, the coke particles and the lining (wall) by convection from the gases and by conduction from the lining of the kiln. The quantity of heat corresponds to that given up by the gases and the coke particles minus the heat lost by radiation from the casing of the kiln.

The process can be expressed by

$$Q_{\text{Gas}} = Q_{\text{Radiation kiln casing}} = Q_{\text{Radiation G.M.}} + Q_{\text{Radiation C.M.}} + Q_{\text{Radiation W.M.}}$$
$$+ Q_{\text{Convection G.M.}} + Q_{\text{Conduction W.M.}} \quad .. \quad .. \quad (50)$$

$Q_{\text{Radiation G.M.}}$—This has already been calculated.

$$Q_{\text{Radiation G.M.}} = 330,000 \text{ Kcal./m.h.}$$

$Q_{\text{Radiation C.M.}}$—This, also, has already been calculated

$$Q_{\text{Radiation C.M.}} = 451,000 \text{ Kcal./m.h.}$$

$Q_{\text{Radiation W.M.}}$—For the calculation of the heat radiated to the material by the lining, the equation of Stephan and Boltzmann is written

$$Q_{\text{Radiation W.M.}} = F_m . C . \alpha \left[\left(\frac{T_w}{100} \right)^4 . \rho_w - \left(\frac{T_m}{100} \right)^4 . \rho_m \right] . \phi_1$$
$$+ F_m . C \left[\left(\frac{T_w}{100} \right)^4 . \rho_w - \left(\frac{T_m}{100} \right)^4 . \rho_m \right] . \phi_2 \quad .. \quad .. \quad (51)$$

ϕ_1 and ϕ_2 are determined from *Fig. 26.*

Substituting we have

$$Q_{\text{Radiaton W.M.}} = 3 \cdot 67 \times 4 \cdot 70 \times 0 \cdot 3651 \left[\left(\frac{1603}{100} \right)^4 \times 0 \cdot 821 - \left(\frac{1174}{100} \right)^4 \times 0 \cdot 759 \right.$$
$$\times 0 \cdot 410 + 3 \cdot 67 \times 4 \cdot 70 \left[\left(\frac{1603}{100} \right)^4 \times 0 \cdot 821 - \left(\frac{1174}{100} \right)^4 \times 0 \cdot 759 \right] \times 0 \cdot 590.$$

$$Q_{\text{Radiation W.M.}} = 103,000 + 396,000 = 499,000 \ \text{Kcal./m.h.}$$

$Q_{\text{Convection G.M.}}$—This has already been calculated.

$$Q_{\text{Convection G.M.}} = 15,260 \ \text{Kcal. m.h.}$$

$Q_{\text{Conduction W.M.}}$—Kirsch's method is again used to calculate the heat transfer distribution from the temperature distribution at the surface of the lining during a revolution of the kiln. In this manner we have for the heat flow at the i-th stage for the assumed approximate temperature distribution

$$q_{0i} = C_i \sqrt{\omega . \lambda . c . \gamma}$$

in which

$$\omega = \frac{2\pi}{t_0} = 289 \cdot 84 \text{h}^{-1},$$
$$\lambda = 1.5 \ \text{Kcal./m.h. deg. C.,}$$
$$c = 0 \cdot 240 \ \text{Kcal./kg., and}$$
$$\gamma = 2250 \ \text{kg./m}^3.$$

Therefore $\sqrt{\omega . \lambda . c . \gamma} = 484 \cdot 53.$

TABLE 17.—VALUES OF C AND q AT THE i STAGES AT CROSS SECTION II.

Stage	C_i	q_i Kcal/m² h	$q_i + q$stationary Kcal/m² h	Stage	C_i	q_i Kcal/m² h	$q_i + q$stationary Kcal/m² h
0	− 97·5	− 47·242	− 40·822	6	+ 75·1	+ 36·388	+ 42·808
1	− 38·5	− 18·654	− 12·234	7	+ 54·9	+ 26·601	+ 33·021
2	+ 2·8	+ 1·356	+ 7·776	8	+ 21·4	+ 10·369	+ 16·789
3	+ 21·6	+ 10·466	+ 16·886	9	− 20·3	− 9·836	− 3·416
4	+ 50·7	+ 24·566	+ 30·986	10	− 61·1	− 29·605	− 23·185
5	+ 69·2	+ 33·529	+ 39·949	11	− 124·2	− 60·179	− 53·759

The values for C and q at the twelve stages are given in *Table* 17. Taking into account the stationary heat flow, which is 6,420 Kcal./m².h. at cross section 11, we have all the data required to plot the curves shown in *Fig. 27*, which are constructed in the same manner as those for cross section 6 in *Fig. 23.*

The mean heat flow found in this way is

$$q_{\text{Conduction W.M.}} = 32,300 \ \text{Kcal./m².h.}$$

If we multiply this value by the area of the surface of the lining in 1 m. length of kiln from which heat flows into the material and make use of the " unevenness factor " β, which is deduced in the same way as previously for cross section 6
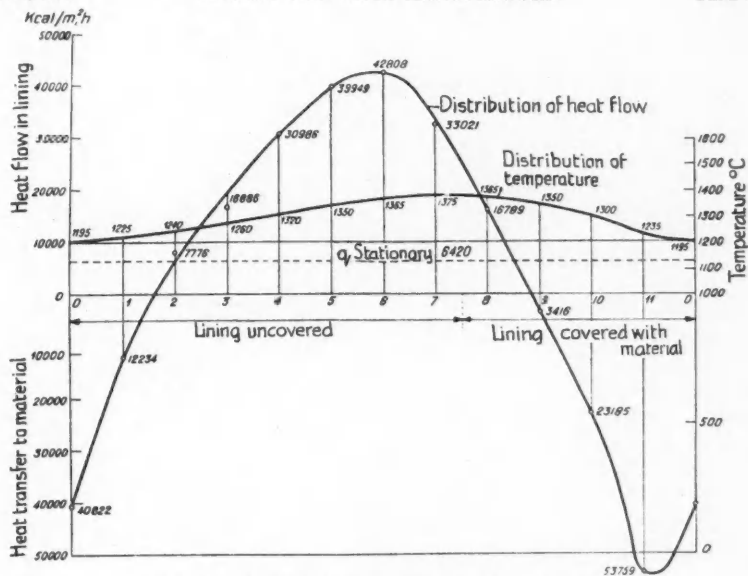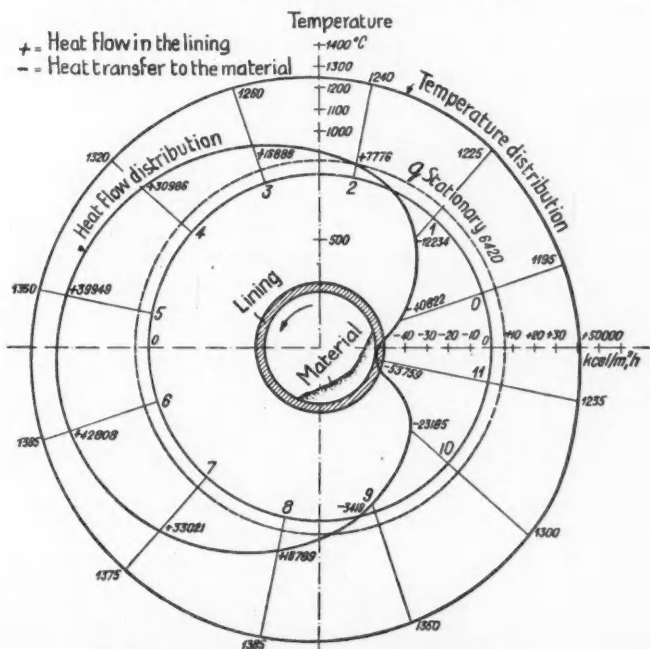
Fig. 27.—As Fig. 23, for cross-section No. 11.

Fig. 28.—As Fig. 27, shown in cross-section.

but which owing to the greater unevenness at cross section 11 has the higher value of 3·4, we obtain

$$Q_{\text{Conduction W.M.}} = q_{\text{Conduction W.M.}} \cdot F_m \cdot \beta$$

or

$$Q_{\text{Conduction W.M.}} = 259,000 \text{ Kcal./m.h.}$$

Fig. 28 is a representation of heat flow and temperature distribution corresponding to that given for cross section 6 in *Fig.* 24.

We are now able to set forth the heat transfer to the material for 1 m. length of kiln.

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Kcal./m.h.

$Q_{\text{Radiation G.M.}}$	=	330,000
$Q_{\text{Radiation C.M.}}$	=	428,000
$Q_{\text{Radiation W.M.}}$	=	499,000
$Q_{\text{Convection G.M.}}$	=	15,000
$Q_{\text{Conduction W.M.}}$	=	259,000

</div>

$$Q_{\text{Gas}} - Q_{\text{Radiation kiln casing (calculated)}} = 1,531,000 \text{ Kcal./m.h.}$$

From the experiments we have

<div style="text-align:center">

Kcal./m.h.

$Q_{\text{Gas (experimental)}}$	=	2,009,000
$Q_{\text{Radiation kiln casing (experimental)}}$	=	60,000

</div>

$$Q_{\text{Gas}} - Q_{\text{Radiation kiln casing (experimental)}} = 1,949,000 \text{ Kcal./m.h.}$$

The heat transfer from the gases and the coke particles, the heat transfer to the material, and the radiation losses from the kiln casing are shown diagrammatically in *Fig.* 29.
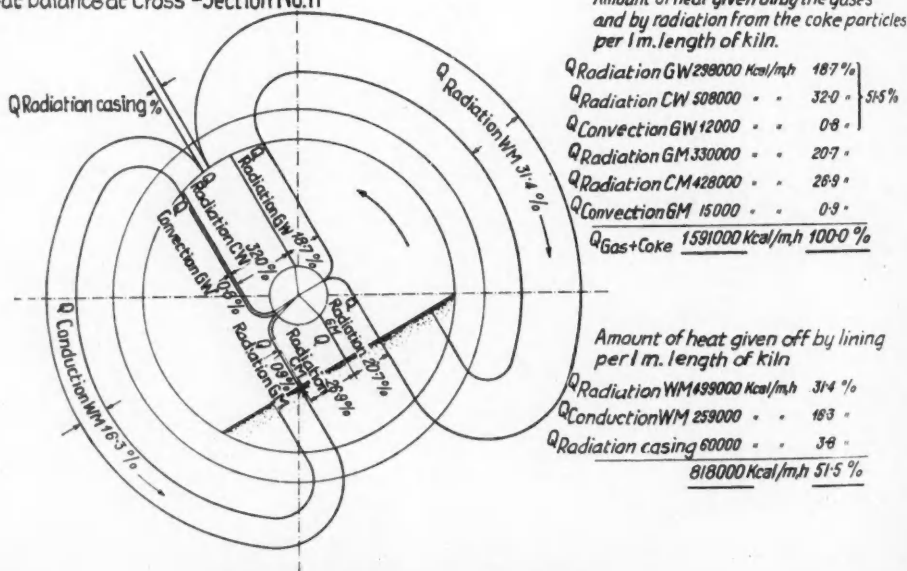

Fig. 29.—Heat balance at cross-section No. 11.

(5) Conclusions with regard to the Design of Rotary Kilns.

On the basis of the experimental investigation and the theoretical study of the heat transfer phenomena, we are able to make certain recommendations with respect to the points which it is most necessary to bear in mind in designing an efficient rotary kiln for burning Portland cement clinker.

As the practical conclusions to be drawn from the work can best be demonstrated by means of an example, it will be assumed that a kiln is to be designed for which the output and coal consumption have already been laid down. We shall now consider how the principal dimensions of the kiln are to be determined.

The first step is to select the diameter of the burning zone, having due regard to the inclination and the speed of rotation of the kiln. As this dimension determines the size of the combustion chamber, it might be thought that the diameter of the burning zone would be given by the quantity of pulverised coal which it is proposed to burn as completely as possible per unit of time. Practical experience has shown, however, that this is not the case, because in any rotary kiln much more coal can be burned without smoke than is necessary for the maximum output. On the other hand, we know that in kilns with a relatively narrow burning zone the durability of the lining leaves much to be desired. This is easy to understand in view of the manner in which heat is given up by the gases in the burning zone and transferred to the material. We have examined this process in detail in the foregoing pages, taking as our starting point the fundamental equation

$$Q_{Gas} = Q_{Radiation\ G.W.} + Q_{Radiation\ G.M.} + Q_{Radiation\ C.W.}$$
$$+ Q_{Radiation\ C.M.} + Q_{Convection\ G.W.} + Q_{Convection\ G.M.} \qquad \cdots \qquad \cdots \quad (41)$$

Our investigation has shown that a diminution of the diameter of the sintering zone must result in higher gas temperatures if coal consumption is kept constant. At the same time, it is clear that higher gas temperatures must lead to higher temperatures in the exposed lining, and this explains the inadequate durability of the lining in kilns with relatively narrow burning zones. However, the selection of a wider burning zone than absolutely necessary is to be avoided, since the lower temperature of combustion would be associated with reduced temperature gradients between the gases and the material and between the gases and the lining of the kiln, which would in turn seriously compromise the efficiency of the kiln.

Having determined the diameter of the burning zone on the bases of the foregoing considerations and with due regard to the dimensions of the kiln used in these experiments, which have been shown to be by no means unfavourable, the next step is to decide whether the pre-heating zone shall have the same diameter as the sintering zone, or whether, following the practice of certain kiln constructors, it shall have a reduced diameter.

The calculation of the heat transfer from the gases has shown that in this part of the kiln the radiation from the gases is still of the greatest importance. It would therefore appear to be advantageous to promote heat transfer by radiation from the gases by retaining the diameter of the burning zone and the thick layer of gas which this ensures, rather than to attempt to improve the less im-

portant heat transfer by convection by increasing the velocity of the gases. Another factor in favour of retaining the diameter of the burning zone is that low gas velocities are particularly desirable in this part of the kiln where the materials tend to produce dust.

The length of the kiln can be determined from the curve in *Fig.* 15, which shows the heat transfer at the various points along the kiln in Kcal./m²., so that for the desired exit-gas temperature the raw material leaves the zone in which the chains are fitted with a residual moisture content of 5 to 10 per cent.

The drying zone also should preferably have the same diameter as the burning zone, as the raw material usually packs to some extent in the chains and the desired increase in gas velocity is thus achieved without special measures. The length of the drying zone is given by the surface area of the chains which is required to dry the slurry to the desired extent at the given exit-gas temperature. The surface area of the chains will depend upon their arrangement and the diameter of the links.

Summary.

The heat balance of the rotary kiln for burning Portland cement and the thermo-technical processes within the kiln have been investigated.

In order to draw up a complete heat balance knowledge of the heat effect is required in addition to the measured values for heat input and heat losses, and special attention has therefore been devoted to an exact determination of this factor on the basis of the results obtained in recent research.

The process of combustion in the pulverised coal flame was investigated by sampling and analysing the gases. The results made it possible to calculate the mean combustion ratio for each sampling point and to plot contours of equal combustion ratio.

The information gained in the experimental investigation of heat transfer and combustion in the kiln were used for the calculation of heat transfer distribution along the axis of the kiln. The resulting curve is of considerable practical importance.

Detailed examination has been made of the heat-transfer conditions at three characteristic cross sections of the kiln. The numerical calculation was not possible in respect of the drying zone, which is provided with chains for the purpose of improving heat transfer by convection ; but for the pre-heating and burning zones it was found possible to make certain simplifying assumptions and to carry out the calculation with their help. It was found that in the hot zones of the kiln the heat is transferred to the material mainly by radiation, the exposed part of the lining acting as an indirect source of heat. In the cooler parts of the kiln the importance of radiation diminishes and heat transfer by convection gradually becomes predominant. The results obtained have been used as the basis for certain recommendations with regard to the design of kilns.

partly explained by the results of previous research.   The calculations are based upon the results of experiments carried out in 1935 with a rotary kiln at the cement works of the Holderbank-Wildegg A.-G.
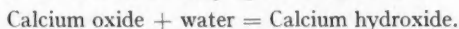
Design and Operation of Modern Lime Works.—XIII.*

By N. V. S. KNIBBS, D.Sc.

THE HYDRATION OF LIME.

The Process of Hydration.

THE hydration of lime consists in carrying out the reaction

Calcium oxide + water = Calcium hydroxide.

It is therefore a reaction between a solid and a fluid to form a solid, and for complete reaction to occur it is necessary for the fluid reactor—water or steam—to find its way to every particle of lime and to remain in contact with it for a sufficiently long period. In the ordinary way lime, when it is slaked, is in large or small pieces, and not in the form of a fine powder, and if it were not highly porous only the outside skin would be acted upon by the water and reaction would be extremely slow. Lime can be obtained in a non-porous condition by fusion and it is then extremely slow in slaking, even when quite pure. Ordinary slaking or hydration therefore depends on the porosity of the lime.

If a piece of compact limestone is burnt to lime at the lowest possible temperature the size of the lime is almost the same as that of the stone. Compact and non-porous limestone has a density of 2.71, so that a litre of limestone weighs 2,710 grammes. On burning to lime the true specific gravity of the lime varies somewhat, but many commercial limes approximate to 3.2, so that the lime from the litre of limestone occupies $2.710 \times 0.56 \div 3.2 = 475$ millilitres, and the pore space in the piece of lime is 52.5 per cent. In commercial operations the temperature of burning is always such that there is a reduction of volume, which varies both in different limestones and with different times and temperatures of burning. On the other hand, all limestones are to some extent porous, and this again varies widely. The initial porosity of the stone therefore tends to balance the effect of shrinkage on burning, and commercial limes generally have porosities ranging around 52 per cent. For example, measurements made on 57 commercial high-calcium limes in the United States showed a range of porosity from 36 to 66 per cent., but most of them were between 51 and 59 per cent. and the majority were between 53 and 57 per cent. Similar measurements on English limes are not available, but lime from carboniferous limestone is less porous and lime from the chalk more porous than most of the United States limes.

If on immersing in water the pores in a lime of 55 per cent. porosity were to fill completely with water the weight of water would be 55 to a weight of lime of $45 \times 3.2 = 144$, so that the water absorbed would be 38 per cent. of the weight of the lime, which is more than the amount theoretically necessary to hydrate it. Actually the pore space is not all filled on immersion. Some of it fills almost

instantaneously, after which there is a more gradual absorption of water and outflow of air which continues for a considerable time ; even after long soaking measurements show that the pore space (calculated from the apparent and true densities of the lime) is not filled with liquid. Consequently lime made from a compact stone will not absorb sufficient water for its hydration, even assuming all the water absorbed were to react with it. In practice, owing to evaporation by the heat of reaction, it is necessary to provide much more water than the amount required for actual combination, the excess amount depending on the purity and reactivity of the lime, and it is found that only highly-porous and impure limes will absorb enough water for complete reaction and heat dissipation.

Lime may be hydrated to form dry powdered calcium hydroxide or to form a suspension of calcium hydroxide in water—milk of lime or lime putty. The procedure and physical conditions of the reaction necessarily differ in the two processes, and they will be discussed separately. It is desirable to reserve the term " slaking " for the formation of a milk or putty (wet hydration) and to use the term " hydration " for the production of a powder (dry hydration).

In the majority of its uses lime is employed wet, as milk of lime or lime putty, but because both these forms contain much water it seldom pays to transport them far. Nevertheless, just as ready-mixed concrete is now produced at central plants in some large cities and delivered ready mixed for immediate placing, so both lime putty and lime mortar are made and delivered ready for use. At the lime plant itself, however, the hydroxide produced is nearly always in the form of a fine powder which is ready for immediate use, and which conforms to the standards of purity and physical properties required by the user.

Slaking, or Wet Hydration.

When lime is slaked to a milk or putty the nature of the product obtained depends upon the properties of the lime and the procedure adopted in slaking. In most instances the product desired, whether it is milk of lime or lime putty, contains calcium hydroxide in the maximum possible degree of dispersion, so that the milk of lime is slow in settling and the putty, for a given consistency, contains the maximum amount of water. To attain a high degree of dispersion it is necessary to avoid conditions which produce " burning " and " drowning,"[1] and these conditions vary with different limes. When a large lump of lime is wetted the water soaks in and starts to react with the lime in the interior. What then happens depends on the lime. In some rapidly-reacting limes the sudden development of heat by the reaction causes immediate fracture of the lump by the stresses set up through unequal expansion. In somewhat less reactive lime the heat evolution is more gradual and it does not cause fracture, but the increase of volume that accompanies hydration in the interior of the lump soon breaks up the lump and allows access of water to the interior, and in either case hydration takes place mainly in the presence of excess of water, giving a highly-dispersed

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[1] "Cement and Lime Manufacture," July, 1937, page 204.

colloidal type of hydroxide. When the lime is slaked in bulk, however, there is a mass of lime made up of many lumps lying closely together. If it is left undisturbed this mass reacts with the water absorbed and each lump may break up, but the formation of a paste of hydrated lime on the outside of the mass soon prevents the entry of water to the interior. Under such conditions the lime in the interior of the mass, having insufficient water for complete hydration and for the dissipation of the heat of hydration, becomes " burnt," and not only may it be incompletely hydrated but the hydrate formed is crystalline or " sandy "—not dispersed and colloidal. To avoid this happening it is necessary to have sufficient agitation and sufficient water present to ensure that hydration of each particle takes place in the presence of liquid water. At the other extreme, if lime in small pieces is agitated with a large amount of cold water the phenomenon of " drowning " may occur, resulting in a gritty product of low dispersion.

The optimum conditions of slaking are therefore those which will prevent overheating and hydration in the absence of liquid water and those which will avoid " drowning." These conditions depend on the nature of the lime and consequently they must be adapted to the type being slaked. A pure, highly-reactive lime hydrates so rapidly that it requires violent agitation to prevent local drying out and " burning," and such lime is very difficult to slake successfully by hand in large quantities. It requires a well-agitated slaking machine. On the other hand, slow-slaking lime should not be agitated with a large quantity of cold water, at least until it has commenced to react. It may be agitated immediately with water raised to boiling point, or it may be placed in cold water and left stagnant until it becomes hot through reaction. If still slower in reaction, the quantity of water must be limited and added gradually as hydration proceeds.

Slaking Plants.

Slaking plants to make milk of lime often consist of a tank in which is suspended a grid or screen into which the quicklime is charged in lump form. The contents of the tank are stirred mechanically or by air, whilst steam may be used both to stir the contents and to heat the water to hasten slaking. With most commercial limes slaking is rather slow unless the water is heated, because in the large excess of water used the initial rise of temperature due to adsorption[2] is very small. Furthermore, in many chemical uses slaking takes place not in pure water but in a solution, for example of sodium carbonate, which decreases the rate of slaking. The grid retains cores and unhydratable lime, which are removed at intervals.

In recent types of plant the lime is agitated with water in a mixing vessel and the milk with impurities passes through a screen or through sand settling tanks where the impurities are screened or settled out.

Plants to produce lime putty for building purposes generally consist of a milk of lime plant, as already described, and large storage tanks to which the milk is pumped and where the excess water is removed either by settling or by drawing it off through perforated tubes covered with a filtering medium. Putty is discharged

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[2] " Cement and Lime Manufacture," July 1937, page 201.

as required through large valves into delivery vans or mixers, or to plants where it is mixed with sand to produce ready-mixed mortar. Some difficulty has been experienced in these unagitated storage tanks due to the putty solidifying and refusing to flow out even though it is not too stiff when agitated or " knocked up." Local agitation just above the outlet valve might be of assistance.

For many years ready-mixed lime mortar has been made in mortar pans or edge-runner mills by grinding and mixing together lime and sand, cinders, clinker, or other siliceous material. The lime may be slaked first or it may be put directly into the pan with the clinker, etc., and water, and it should be ground sufficiently to break up the lime finely so that incompletely hydrated pieces are too small to do serious damage in the mortar after application. Mortar pans are often employed to use up " lime ashes "—the small lime mixed with fuel ash screened from lime made in mixed-feed kilns.

Dry Hydration.

Dry hydration is the process of producing calcium hydroxide free from dele-terious quantities of unslaked lime and other impurities, and without so much excess water that it will not run freely. The initial rise of temperature already mentioned[2] makes an active lime commence hydration rapidly, and the heat produced during the hydration of pure lime is sufficient to evaporate a large excess of water. Theoretically a lime containing 100 per cent. calcium oxide requires 32 per cent. of its weight of water to form the hydroxide, and there is enough heat to evaporate a further 39 per cent., assuming lime and water are mixed at 0 deg. C. If there is not sufficient water to use up the excess heat evolved, and if that heat cannot get away freely by conduction, radiation, etc., the temperature of the lime is increased above 100 deg. C. For example, the heat generated by mixing pure lime with the theoretical amount of water is sufficient to raise the temperature well above the dissociation point of 537 deg. C., and if the water is in the form of steam the sensible heat generated is still greater. At temperatures much lower than this the lime is " burnt." When water is added to lime in lump form it is impossible to wet the lime uniformly, and some parts may remain quite dry with the result that steam evolved from the parts receiving most water reacts with the dry lime and produces overheating. It is therefore possible to have " burning " even in lime to which sufficient water has been added, if that water, either through inadequate mixing or through the use of lime in large lumps, is not uniformly distributed.

It is a well-recognised fact that the lime hydrated by water vapour is much more sandy, or crystalline and less colloidal than lime hydrated in water and, because much of the hydration reaction producing dry hydrate must necessarily take place in the absence of liquid water, hydrated lime when mixed with water produces a less colloidal and workable putty and a more rapidly settling milk than lime slaked directly to a milk or putty. To make a dry hydrate having the maximum possible degree of dispersion in water it is therefore desirable to arrange the hydration reaction so that as much of it as possible takes place with liquid water present, and so that at no time does the temperature exceed boiling point,

thus avoiding the destruction of the colloidal nature of the hydrate by a high temperature. It is possible, of course, to hydrate to a putty and then to dry the putty by heat, but hydrate so formed is not at present producible at a competitive cost. In commercial processes of hydration heat is dissipated by radiation, conduction and air cooling, and by evaporation of the excess water, and those processes which involve the least loss of heat by radiation, air cooling, etc., and the most by evaporation, and which further avoid heating above 100 deg. C., necessarily produce the best hydrate.

Hydrators and Processes of Hydration

The dry hydration of lime was originally carried out by spreading lumps on the floor and watering them with a hose or otherwise. The lime must be turned over by rakes and the whole process is extremely dusty unless the lime is very slow-slaking, in which case the process is ineffective because the lime does not " fall " quickly enough to give a reasonable output in the available space. Hydration by hand is still employed at some small plants, but it is of no general interest. It is also used in the hydration of slow-slaking hydraulic limes which are wetted, piled up, covered with sand to conserve the heat, and left for some days to hydrate.

Mechanical hydrators are of two types, batch and continuous. The division between the two is not clear-cut, because some continuous hydrators discharge to silos where hydration is completed and therefore the whole operation of hydration is discontinuous. Furthermore, there is one hydrator which is actually designated " batch-continuous." However, it is convenient to divide hydrating machines and processes into the two classes, and those classified here as " continuous " are hydrators which can continuously produce in the machine itself hydrated lime ready for separation, so that the whole operation from feeding the quicklime to the storage or bagging of the finished hydrate (ready for immediate use) is continuous.

In batch machines definite quantities of lime and water are weighed or measured and mixed together in some kind of mixer. The amount of water is adapted to provide sufficient for hydration and for evaporation, the latter quantity depending on the conditions of hydration and the quality of lime used. The advantages claimed for batch hydration are simplicity of operation and more exact hydration due to the better proportioning of lime and water, but it is theoretically just as easy to feed lime and water in definite proportions continuously as intermittently. Practically, however, it is easier to weigh and measure accurately in batches, and therefore, if hydration is controlled merely by proportioning the mix, there is an advantage in operating in batches. Unfortunately, in practice there is no way of ascertaining the exact amount of water required except by a trial in the hydrator itself, the product being tested for free lime and free water. These tests take a considerable time and meanwhile hydration would be held up or continued without knowing whether the amount of water is correct. Moreover the amount of water required varies with atmospheric conditions as well as with a change in the quality of the lime. Exact hydration is therefore not com-

mercially feasible by this means, but neither is it necessary in the ordinary way, and in practice, given sufficient experience in operation, batch hydration produces a good hydrate.

Hydration in Silos.

The simplest type of batch hydrator is simply a silo or bunker. Lime and water are mixed in the right proportion, dumped into the silo and left for a period sufficient for reaction. The product is then taken out and put through one of the
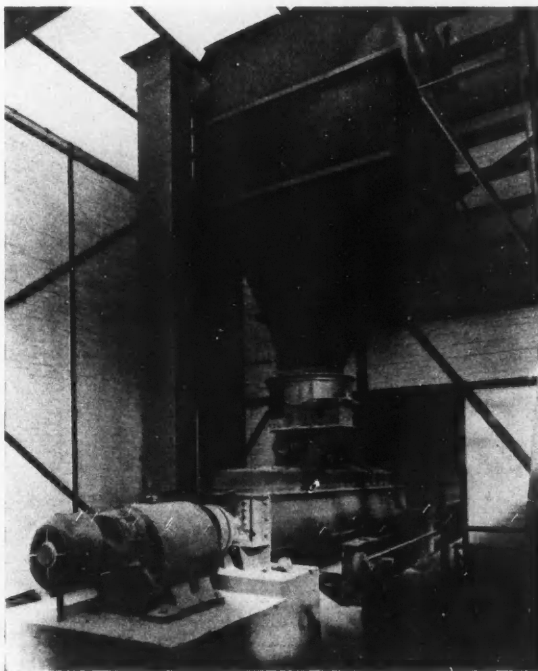

Fig. 58.

processes of after-treatment, which will be described later. This procedure of hydrating lime has been used to a considerable extent for the eminently hydraulic limes used on the Continent. These limes do not swell much in hydration, and they absorb enough water for their complete reaction. When purer limes are treated in the same way two difficulties arise. In the first place they will not absorb and retain enough water for their hydration, including the amount evaporated in the process. When mixed with sufficient water and dumped in a silo the water runs to the bottom, giving uneven hydration. In the second place,

the swelling during hydration may burst the silo, or the hydrate becomes packed together so hard that it is very difficult to discharge it and it may be necessary to remove it with pick and shovel.

In spite of these difficulties the process is being used for the hydration of a high calcium lime in the United States.[3] The first difficulty is overcome by using a finely-ground lime which forms a slurry with comparatively little tendency to segregation. The second difficulty seems to be of less importance in silos of large diameter, and in this instance it does not appear to be insuperable. Nevertheless, the process is not being used elsewhere for the same kind of lime.
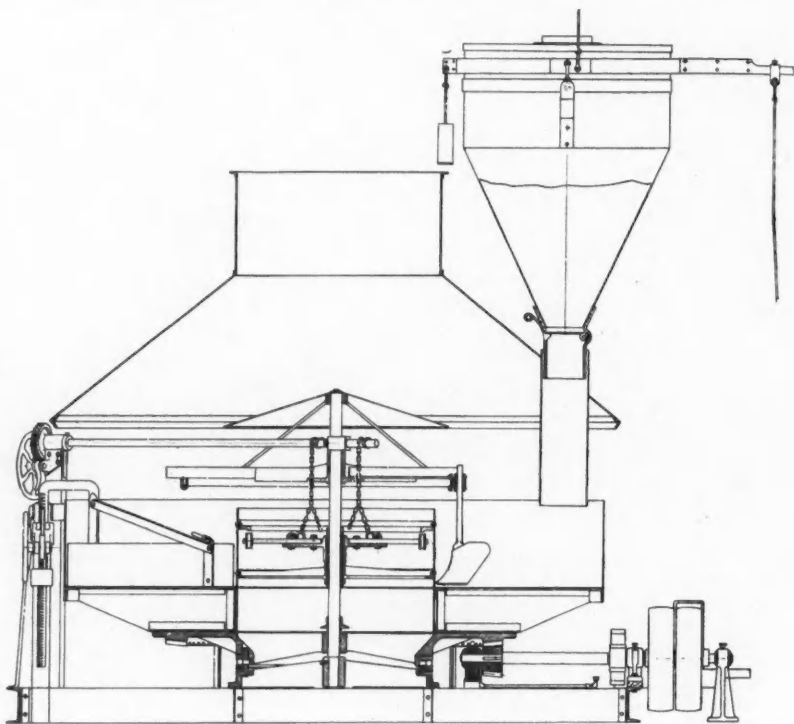

Fig. 59.

THE KRUPP HYDRATOR.—The Krupp hydrating process is essentially a silo process, but the admixture of lime and water is carried out in a " slaking screw " (shown in *Fig*. 58) which is large enough to allow part of the hydration reaction to take place before the material falls into the bunker ; there is thus less expansion in the silo and the partially-hydrated lime will hold in absorption sufficient water

[3] Carson—U.S.Ps. 1, 244, 421 and 1, 613, 341.

to complete the reaction. The lime is crushed to about $\frac{1}{2}$in. size before entering the screw and water is sprinkled on it at different positions along the screw.

THE CLYDE HYDRATOR.—This machine, which has been in use since hydrate was first sold on an extensive scale in the United States, is still the most widely-used batch hydrator. It consists of a wide shallow pan which rotates about a vertical axis like a mortar pan, and in which are suspended stationary ploughs
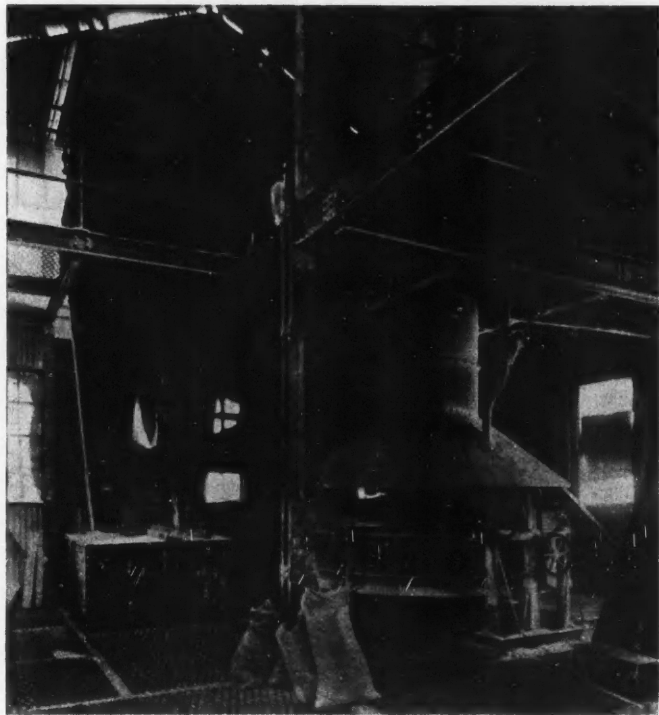

Fig. 60.

(as shown in *Fig.* 59) which sweep the whole area of the pan, turning the contents over and over, and mixing them. A batch of lime is weighed, dumped through the chute into the pan, and a measured amount of water is sprayed on to it and mixed with it by the ploughs. When hydration is judged to be sufficiently complete a door at the centre of the bottom of the pan is opened and the hydrate falls through into a hopper beneath. A feature of the machine is that it is always open, as shown in *Fig.* 60, so that the contents can be inspected at any time. The dust and steam rise through the hood covering the whole area of the pan into a

wide duct leading through the roof. Alternatively, to create a better draught and to recover the dust, the duct may be connected to a spray washer, but the wide opening above the pan makes it necessary to deal with a large volume of air in the washer, which must therefore be of considerable size. The machine is of robust construction and easy of access for maintenance and repairs. A typical arrangement of a Clyde hydrator with its subsidiary plant will be shown later when discussing the after-treatment of hydrate.
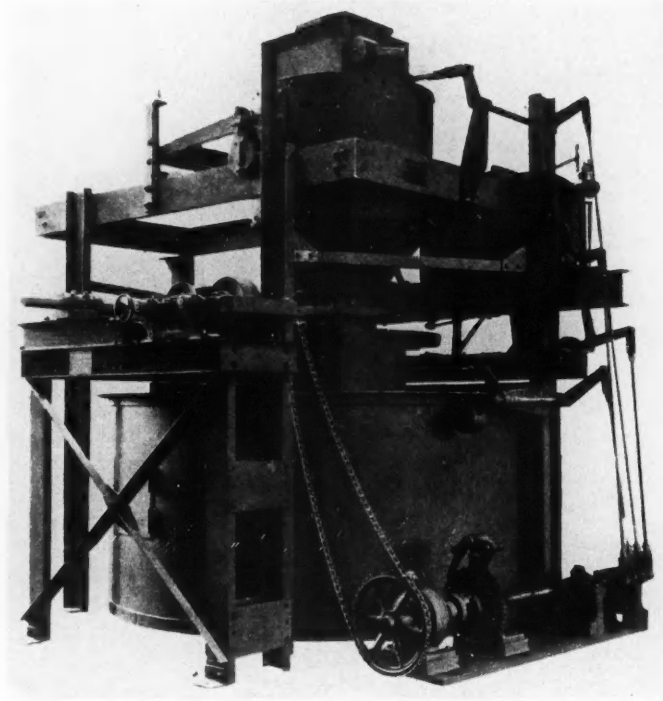

Fig. 61.

THE VULCAN HYDRATOR.—The Vulcan hydrator (*Fig.* 61) is similar in principle, but the pan is stationary and the ploughs rotate about a central shaft. Being stationary, the hydrating chamber can be completely closed but it has a large door that may be opened for inspection. The totally-enclosed plant is much more easily rendered dust-free than the Clyde hydrator. The machine shown in *Fig.* 61 is fully automatic, the various valves controlling the lime, water, and hydrate being operated by cams driven by a ratchet wheel and variable-speed

gear. The time of the cycle—charging, mixing of water, hydrating, and discharging—may be altered by changing the setting of the variable-speed gear. The same machine is manufactured for hand operation, similar in principle to that of the Clyde hydrator.

PRESSURE HYDRATION.—The hydration of lime in an autoclave by steam under pressure has been employed for some years to supply hydrate for sand-lime brick production. The autoclaves generally consist of cylindrical vessels made of boiler plates and arranged horizontally with agitating gear carried on a central shaft passing through glands at each end. Alternatively the whole cylinder may rotate, in which case steam is led in through tubes passing through the glands at the end. The process is necessarily a batch one, and the charging and discharging door must be of sound construction to remain tight under the conditions of operation. The same type of plant has been proposed for the complete hydration of magnesian lime. Pressure hydration by steam produces a crystalline non-plastic type of hydrate unsuitable for most purposes. Its main object is the complete hydration in a short period to a condition in which there will be no subsequent expansion when mixed with sand, formed into bricks, and steamed under pressure.

OTHER BATCH HYDRATORS.—Since practically any form of dry mixing plant may be used as a batch hydrator, there is a number of other types in use or which have in the past been used for the purpose of hydration. One that is of special interest is the Weber hydrator which differs from most others in that it has a double set of stirrers carried on two shafts, somewhat the same as in a pug mill. The principle of operation of them all is the same.

The hydrators illustrated are supplied by the following firms: Fig. 58, Krupp-Grusonwerk; Figs. 59 and 60, International Combustion Ltd.; Fig. 61, Vulcan Ironworks.

(To be continued.)

Cement Tests.

FOR many years the strength of cement or mortar has been tested on specimens made in moulds in the shape of a figure eight. More recently compression tests have been introduced because it is in compression that the materials are normally stressed in constructional work. In addition, a compression test gives more reliable results.

Notwithstanding the careful manner in which the methods of carrying out the tests is laid down, experience has shown that when the same cement is tested in a number of laboratories in accordance with a technique which is most rigidly defined in all its details (temperature at which the specimens are made and stored, amount of gauging water to be used, grading and nature of the sand, length of gauging period, method of filling the moulds, etc.) the mean result varies by 4 per cent. to 15 per cent. between one laboratory and another. In any one laboratory, tests repeated by different men give better agreement with the average result, especially when the specimens are tested in compression.

In *Le Génie Civil* (April 16, 1938), Mlle. Edith Couillaud states that a careful study in nine laboratories, both official and private, has shown the preponderating effect of the tester's personal equation and the urgent need for completely mechanical preparation of the specimens if constant results are to be obtained from the tests. Since filling the moulds by hand is an operation largely influenced by the personal factor, mechanical filling was tried. The mortar, gauged by hand, was filled in small quantities into cubical moulds with 5-cm. edges, and these were subjected to horizontal circular motion of variable frequency. The actual horizontal accelerations were several times the acceleration due to gravity.

In additional tests, mechanical gauging in a small rotary mixer was used. This produced a better and constant degree of homogeneity in the mortar. In these tests, also, the mortar was filled automatically into the rotating moulds, thus dispensing with the personal equation of the tester, except in weighing and supervision.

In this new method of making the specimens, the constituents of the mortar arrange themselves so that the specimens weigh 4 per cent. more than hand-made test pieces, and the average relative deviation, which is a criterion of the accuracy of the tests, and is of the order of 5 per cent. to 7 per cent. in current practice, is decreased to less than 2 per cent. Likewise, the maximum relative deviation in the same number of tests is halved, and the average deviation of the mean of successive gaugings in relation to the general mean is reduced in the ratio 3 : 1. Further experiments are being made to determine the exact effects of the frequency and diameter of the rotary movement, the shape of the distributor, and the mixing and filling times.